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ULTRASONIC DEHYDRATION FOR LIQUID DENTAL MEALS

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes the work accomplished in the successful completion of Phase I of this SBIR Project. It includes:

1. Examination of several options for the use of ultrasonic energy in the dehydration process of liquid dental meals,
2. Identification of parameter ranges for food products and ultrasonic equipment compatible with the dehydration process,
3. Preparation of a list of representative food items that are based on the process parameters and which would be suitable for ultrasonically assisted dehydration,
4. Performance of feasibility experiments using ultrasonic transducers and liquid food products to validate the research findings,
5. Outlining the steps necessary to implement the prototype process and to test the quality of the dehydrated products.

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Preface

This is the final report for Phase I of "Ultrasonic Dehydration for Liquid Dental Meals", which was performed by Technology International Incorporated (TII) under contract # DAAK60-93-C-0023, with the U.S. Army, Natick RD&E Center. This technical data and information are in accordance with the requirements, quintets and schedules as set forth in the Contract Data Requirements list, DD Form1423 and Data Item Description DI-MISC-80711.

Technology International has utilized MIL-STD-1472, Human Engineering Design Guidance for Military Systems, Equipment and Facilities as guidance in developing the optimized drying procedure. MANPRINT (manpower, personnel, training, human factors engineering, and system safety) consideration was integrated into the ultrasonic drying procedures.

Under System Safety, TII applied Safety Engineering and Safety management principles, criteria and techniques as a Formal System Safety Program effort that stressed early hazard identification, evaluation, elimination, or subsequent control to preclude injury or death to the user of material developed for the U.S. Army. All hazards identified during initial contract research are described in the final report. All solutions for identified hazards are also described.

The project officer for this project originally was Dr. Tom Yang. The current project officer is Joseph Cohen, of Natick's Sustainability Directorate.

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ULTRASONIC DEHYDRATION FOR LIQUID DENTAL MEALS

1. Summary

In Phase I of this Project, Technology International, Inc. (T I I) has:

1. Examined several options for the use of ultrasonic energy in the dehydration process of liquid dental meals,
2. Identified parameter ranges for food products and ultrasonic equipment compatible with the dehydration process.
3. Prepared a list of representative food items that are based on the process parameters and which would be suitable for ultrasonically assisted dehydration.
4. Performed feasibility experiments using ultrasonic transducers and liquid food products to validate the research findings.
5. Outlined the steps that are necessary to implement the prototype process and to test the quality of the dehydrated products.

The options for the use of ultrasonic energy included sonification of a bulk mass of fluid using submerged transducers, and the use of ultrasonic nozzles to focus the ultrasonic energy on the fluid to be dried. During Phase I of the project, TII performed work to demonstrate the feasibility of the concept of using ultrasonic energy in an ultrasonic dehydration system (UDS) to improve the process of dehydration of liquid food products. The UDS consists of two primary states;

1. The liquid food products are subjected to an ultrasonic field that causes cavitation in the liquid. This results in the "vaporization" of the product into very small droplets on the order of 1 micron in size. The droplets take the form of a mist that carries the water and small food particles into the air.
2. In order to dehydrate the food product, the mist that results from the ultrasonic process is exposed to heated air, which causes the phase change in the water. After the water is evaporated, the remaining dried food product is collected to be stored for later rehydration.

The experiments conducted in Phase I utilized transducers that were submerged in a tray that contained the food product to be processed. The sonification of the liquid food product created a fine vapor that contained the food particles in solution or suspension (depending on the nature of the food). This method most closely resembles the dehydration method of spray drying. The ultrasonic approach, however, results in finer particles which promote more rapid drying and lower temperatures. In addition, the limitations of spray drying such as clogging and feed considerations do not apply, since ultrasonic energy accomplishes the atomization of the food. Because of the short residence times required, the speed and economy of the process should exceed current freeze-drying techniques, while yielding high quality products.

An alternative configuration was identified that would use ultrasonic nozzles together with a fluid stream. The stream would be atomized and dried rapidly and efficiently. This approach would allow the ultrasonic process to be applied to a variety of pumpable products. The results of this research provide a strong basis for continued development that will lead to a drying system which can be applied to liquid food products, as well as other pumpable fluids.

2. Introduction

Food dehydration is the unit operation in which nearly all the water normally present in food products is removed by evaporation or sublimation, as a result of the application of energy, as in the form of heat, and/or the reduction of environmental pressures under controlled conditions. Dehydration of foods result in savings in mass and usually volume per unit of food value, and also in products with extended shelf lives, as compared with fresh materials. The main considerations of a dehydration process with respect to food products is to remove the water from the food as rapidly and as efficiently as possible with regards to operation costs, and to avoid damage to the food product, thereby retaining the nutritional and organoleptic qualities of the food during the dehydration process, and through its rehydration.

U.S. Army,Natick is interested in developing a method for the dehydration of liquid dental meals that will offer advantages over existing food dehydration methods such as freeze-drying. Such a method will yield higher quality food products while attaining rapid drying rates to maintain economic competitiveness with existing processes. The purpose of the Phase I project has been to identify an innovative dehydration process that is based on the use of ultrasonic energy. This includes the identification of food products that are compatible with the ultrasonic process and to further identify the process parameters for the foods and the equipment.

A review of existing methods of food dehydration was conducted to determine the areas in which ultrasonic would offer benefits regarding such considerations as *efficiency, temperature* requirements and process time. In many processes, the food is exposed to extremely high temperatures, which degrade the quality of the dehydrated product. The use of ultrasonics eliminated the need for these high temperatures, as the energy supplied by the transducers does not raise the bulk temperature of the food products, thus eliminating the possibility of heat damage. The final method chosen by TII incorporates ultrasonic sonification of the liquid food products and a heated air stream to supply the additional energy that is necessary to remove the water from the food. In effect, the ultrasonic process separates the liquid into very small (micron-sized) droplets. This promotes very rapid heat transfer. The ultrasonically-assisted drying methods would yield a process with very short residence times for the food products, thereby lowering the temperature gradients necessary for drying.

TII is developing a system which uses ultrasonic waves incorporated with heated air to dehydrate food products. The ultrasonic energy makes the evaporation of the water from the food more efficient by atomizing the liquid into micron-sized droplets. Ultrasonic energy has been applied to the process of coffee dehydration (Bilenker, 1960). The process was used to defoam the coffee before freeze-drying to improve the crystallization process and to eliminate gold-colored flecks in the granules. It was also used to help extract a concentrate before the final dehydration process. The process developed by TII uses ultrasonic energy to physically separate the liquid food products to allow rapid drying, while eliminating the need for high temperatures to remove the water.

One method that was developed from technology that used sonic pulses that were applied for short durations at very high temperatures is pulse combustion drying which utilizes frequencies from 125 to 150 Hz and outlet temperatures from 540 to 1150 ^{o}C (Ozer, 1993). The method under development at TII relies on high frequency ultrasonic pulses to provide the necessary energy for the dehydration process. The temperatures for drying are considerably lower.

Physical Basis

The physical theory behind the research centers on the acoustical cavitation of liquids. The intense sound waves provided by ultrasonic transducers create alternating regions of compression and expansion in the liquid which form bubbles on the order of 100 microns in diameter. If the bubble is of critical size, as determined by the frequency of the ultrasonic waves, the bubble may implode violently, thus releasing the energy and forming a concentration of heat and energy. The violent implosion of these bubbles produces a localized hot spot on the order of 5,500 ^{o}C. Since this region is small, the heat dissipates quickly. The result is that the bulk of the liquid remains at ambient temperature. As the bubbles at or near the surface implode, micronsized particles can be released into the surroundings if the acoustical pressure of the transducers is of adequate magnitude. Figure 1 illustrates this phenomenum. It is this process, the creation of these micron-sized particles, which is the basis of the ultrasonic dehydration process.

In order for the ultrasonic energy to create the tiny droplets of liquid that contain the food particles, the necessary conditions must exist for acoustic cavitation to occur. The onset of cavitation is a function of the frequency of the ultrasonic transducers, the acoustic pressure of the transducers, and the diameter of the bubbles that are suspended in the solution.

Apfel, 1981, has analyzed these relationships to predict whether or not cavitation will occur in liquids in an acoustic field. He examined four threshold conditions for acoustic cavitation.

1. The Blake Threshold: This provides an expression which gives the minimum acoustic pressure at which a gas bubble of a given radius will grow in a given liquid. The threshold is based on static conditions and does not include dynamic effects.
2. Threshold for Rectified Diffusion: This provides an expression for the minimum acoustic pressure at which a bubble of a given radius will grow to rectified diffusion. This is dependent upon the gas saturation of the participating liquid. The higher the level of gas diffusion, the lower the pressure that is necessary for a bubble of a given radius to grow in the liquid.
3. Transient Cavitation Threshold: This provides threshold pressures for transient cavitation which is due to short-lived bubble motion often characterized by a sudden snapping sound. The threshold is highly dependent on the dynamics of the bubbles in the liquid.
4. Inertial Radius: This expression relates the acoustic pressures at which the inertial effects of a bubble of a given radius will become influential in cavitation

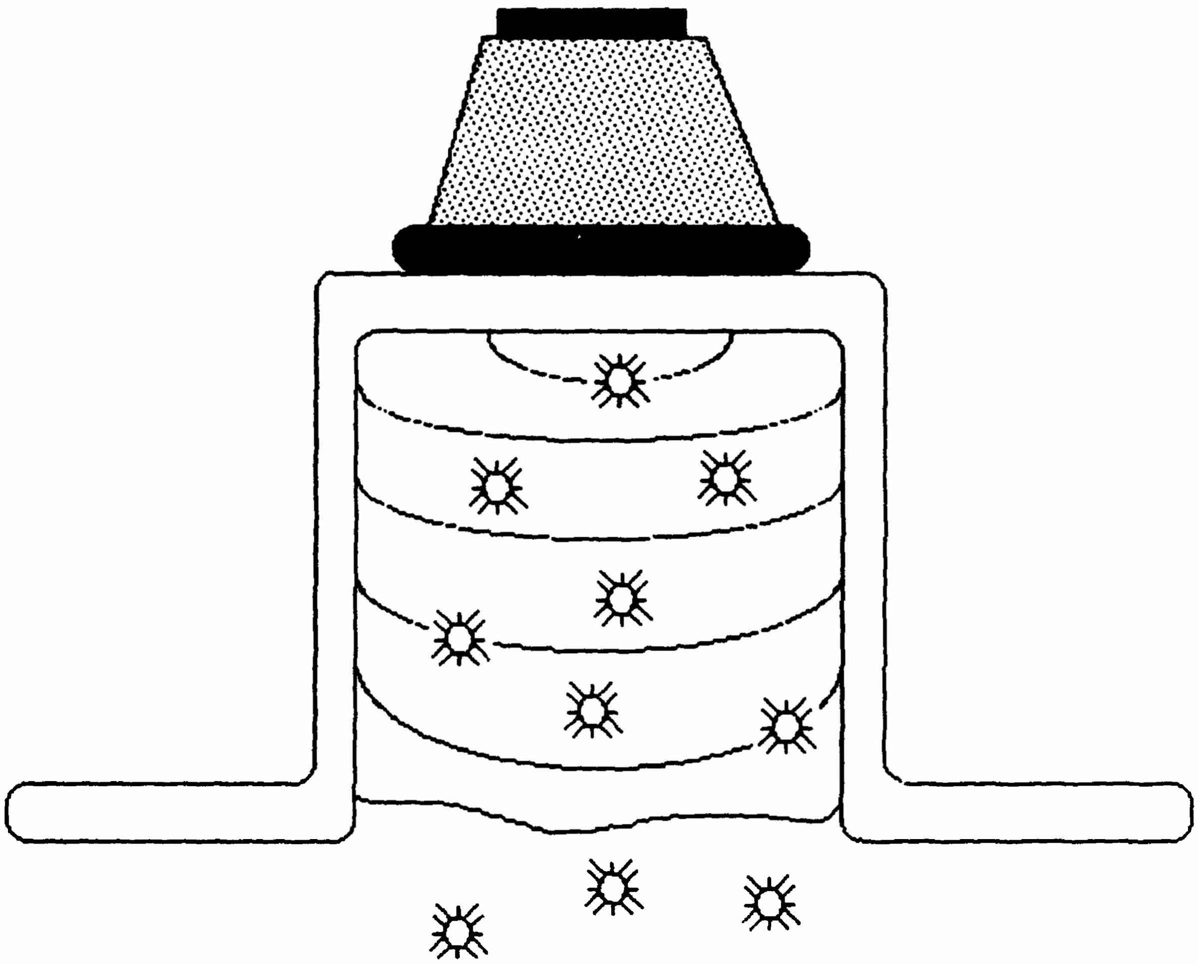

Figure 1. Acoustic Cavitation

prediction. At higher pressures, the inertial effects are cancelled and bubble growth is impeded.

The plot in Figure 2 shows the cavitation thresholds in water for a 40 kHz transducer. The plot is non-dimensionalized with respect to pressure amplitudes and initial bubble radius about which cavitation begins. The lines designate boundaries defined by the above thresholds. The intersection of the curves define regions of different types of cavitation. (Apfel, 1981)

Region A: Only rectified diffusion will lead to bubble growth. As the bubble radius reaches resonance size, oscillations tend to break them into smaller bubbles.

Region B: Bubble growth by rectified diffusion and/or by direct mechanical means may occur, but the initial bubbles will not be transient. Again, as the bubbles grow to resonance size, they tend to break down into smaller bubbles.

Region C: In this region, the bubbles tend to be transient, often with violent collapse due to higher acoustic pressures.

Overview of Dehydration of Foods

The methods used for dehydration of foods may be classified as one of the following:

1. Drying by heated air (convection)
2. Drying by direct contact with a heated surface (conduction)
3. Freeze-drying

The appendix gives an overview of the different methods. The Ultrasonic Drying System (UDS) under development at TII most closely resembles the first classification, drying by heated air.

UDS produces a mist that consists of tiny droplets. The surface area of the liquid that is exposed to the air is of particular interest when considering the ultrasonic dehydration process. The droplet size is about one micron across. As a basis for comparison, compare this process to spray drying methods which produces droplets with diameters of 5 to 10 microns for thin liquids. The heat transfer rate is proportional to the surface area, which in turn is proportional to the square of the diameter of the liquid droplets. For example, one kg of water has a total volume of 0.001 m^3. For the ultrasonic process, with a droplet diameter of of 1 micron, the total surface area is 6,000 m^2. For droplets of 5 micron diameter, the surface area is 1,200 m^2. This corresponds to a heat transfer rate on the order of 5 times greater for the ultrasonic process than for the spray drying. Alternately, for the same heat transfer rate, with the same heat transfer coefficient, the temperature gradient required for the 5 micron droplets would be 5 times greater than the 1 micron droplets. This is a simplification of the heat transfer process, but it does illustrate an important point.

The UDS is like most spray-drying systems, in that the drying mode is primarily through convection and relies on the rapid evaporation of tiny droplets of liquid. The fine nature of the mist produced by the UDS should result in lower temperatures required for the drying process. The end result is a system which

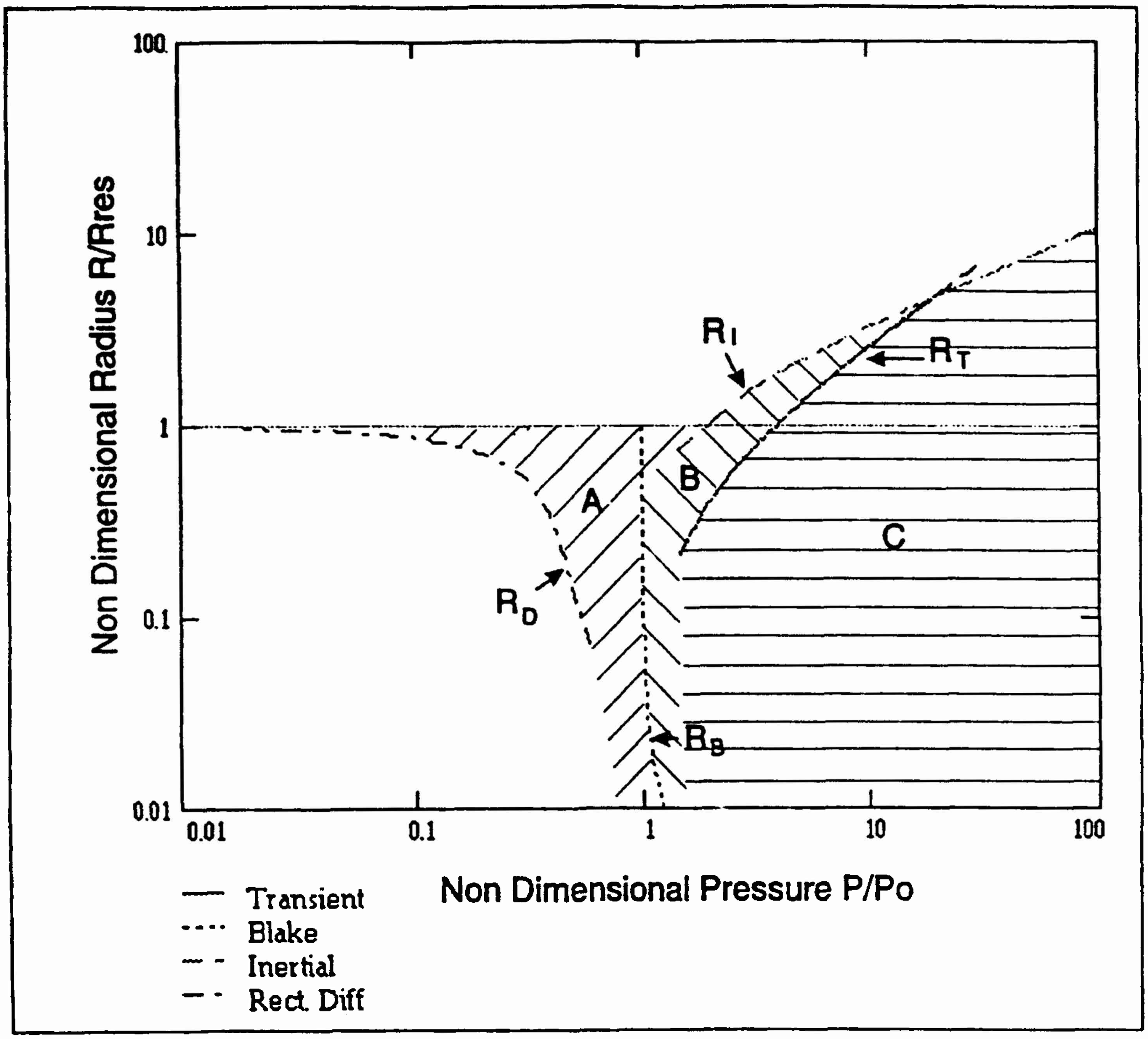

Figure 2. Cavitation Prediction Graph foı 40 kHz Signal

dries liquid foods in the same manner as does a spray drier, with lower temperatures and at operating costs that are lower than freeze-drying.

3. Methods, Assumptions and Procedures

Preliminary Considerations

Among the options for the configuration of the ultrasonic transducers are:

1. Sonification in bulk, in which the transducers are immersed under the fluid being irradiated.
2. Suspended particles, in which the sonic field is applied to falling droplets or a stream of fluid.
3. Ultrasonic nozzles, which could focus the ultrasonic energy either on a bulk of fluid or on a stream of liquid.

In the early stages of Phase I, the use of ultrasonic energy alone was considered for dehydration of the liquid dental meals. Ultrasonic cavitation at lower frequencies was examined and found to be insufficient to produce adequate drying rates. At these lower frequencies, 40 to 80 kHz, the cavitation produced by the bulk sonification of liquids is mainly internal. That is to say, it does not release sufficient amounts of fluid from the surface of the liquid. It was then determined that the use of higher frequency transducers, in the MHz range, would provide the necessary energy that is required to release the liquid from the surface and into the surrounding air.

The configuration chosen for Phase I, proof-of-concept experiment, is sonification of bulk fluid. The transducer array is set on the bottom of a tray which holds the liquid food product to be processed. A picture of the configuration that was used is shown in Figure 3. The only difference is that the experimental equipment utilizes only two transducers, instead of the multiple shown here. This configuration is based on the use of ultrasonic transducers in ultrasonic humidifiers. The humidifiers release very fine particles of liquid in the air stream as a result of the ultrasonic irradiation. The equipment was purchased from Ellis and Watts[1] and modified to hold the liquid food product. The ultrasonic transducers operate at 1.7 MHz and a nominal pressure amplitude of 100 Pa (10 bar). For these values, cavitation will occur when the acoustic field acts upon very small vapor cavities of vapor dissolved in the liquid. Figure 4 is the cavitation threshold plot for the given frequency and pressure amplitude. It shows the range of parameters for which cavitation will occur. It should be noted that the graphs are adequate for fluids of relatively low viscosity. However, for high viscosity fluids, the pressure amplitudes that are required to produce cavitation at the given frequencies would be larger.

The theory behind the experiment is that the high intensity ultrasonic field will produce cavitation in the liquid food product and will cause very tiny droplets of liquid, that contain the solid particles in solution or suspension, to be released into the air. In order for the process to be successful, the tiny droplets must contain the food product which is to be collected as a powder after the water evaporates.

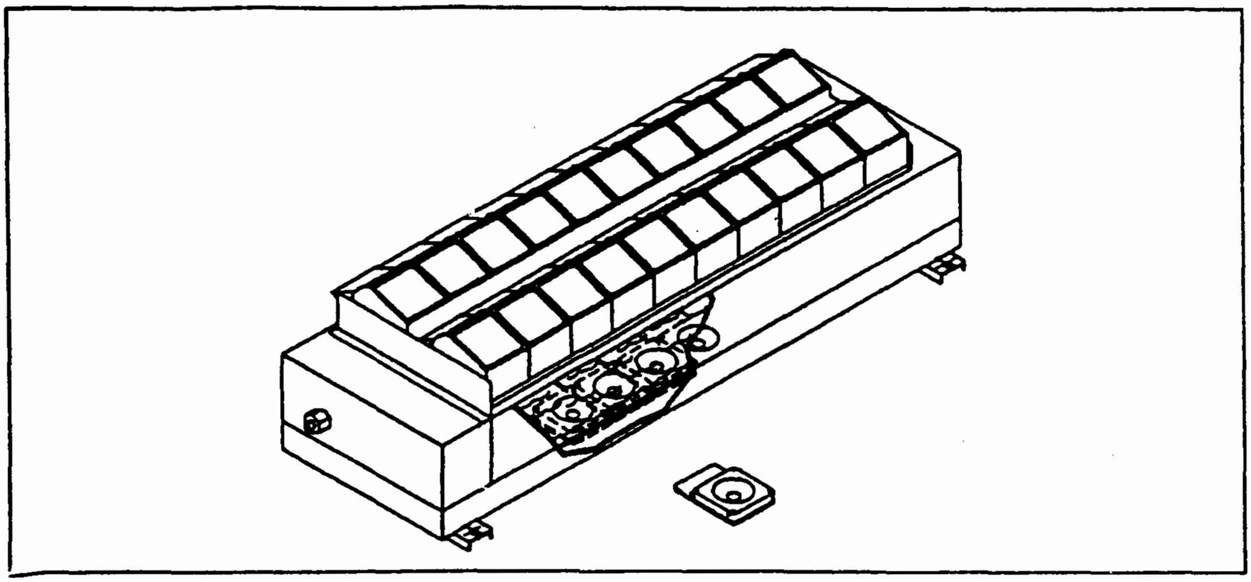

Figure 3. Experimental Ultrasonic Dehydrator

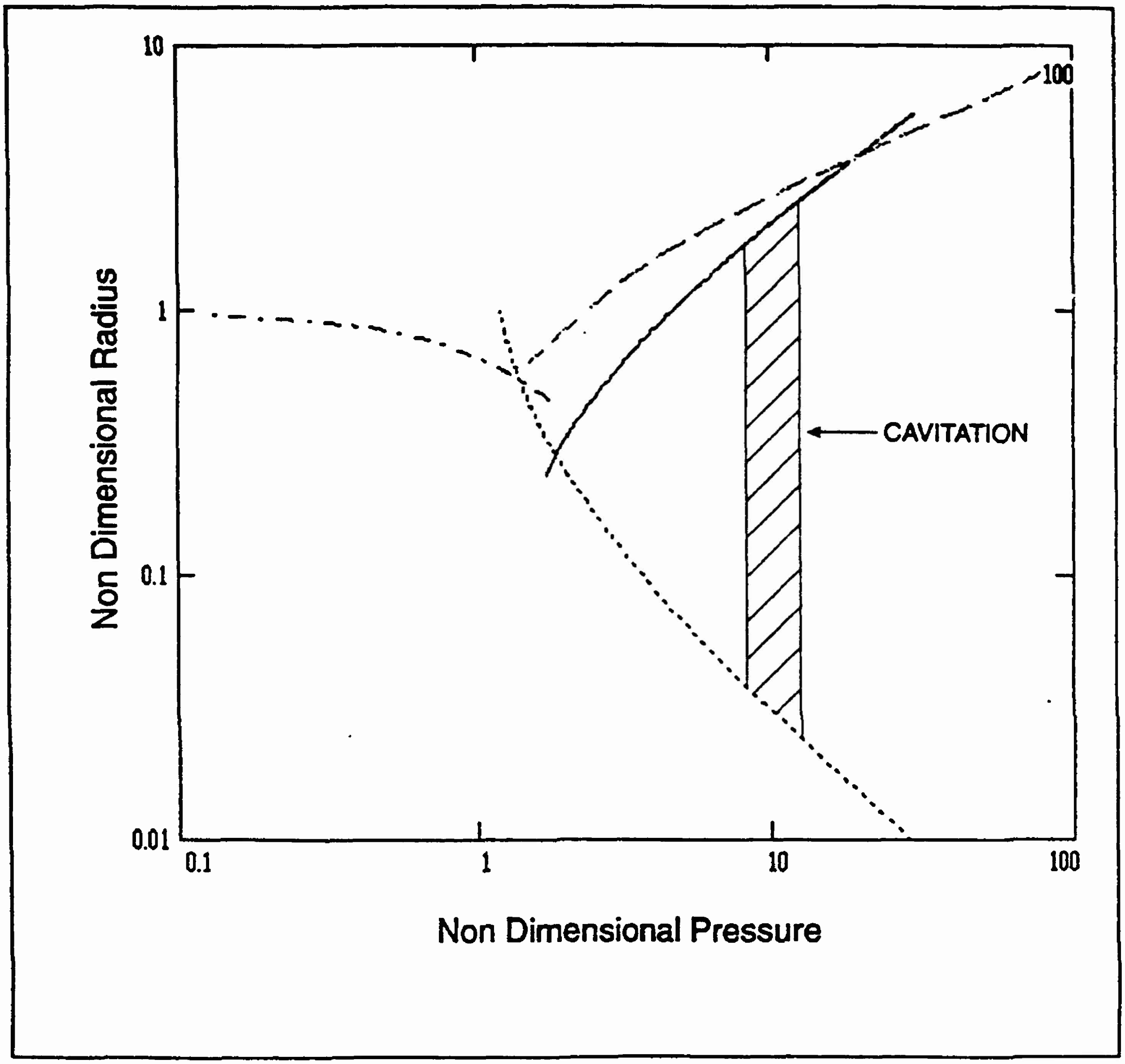

Figure 4. Cavitation Prediction Graph for Experimental Assembly

Requirements for Liquid Dental Meals

The Dept. of Defense has determined the requirements for liquid dental meals that include specific technical characteristics. (Edinburg and Engell, 1988). The meals or rations should satisfy the following criteria:

- The ration should include a breakfast entree and cereal; an entree, starch, vegetable, and dessert for midday and evening meals; and six different flavors of between-meal supplements that are similar to milkshakes.
- The products must be dehydrated and easily reconstituted with either hot or cold water.
- The ration must have a shelf-life of three years or more, without refrigeration.
- The ration must provide at least 2,500 kcal per day and 80% of the Recommended Daily Allowance (RDA) for men who are between the ages of 19 and 51.
- The products must be acceptable in terms of a number of sensory characteristics and must provide adequate satiety.

Additional allowances should be considered if the recipient of the rations is a surgery patient who requires more protein or vitamins to aid in the recovery process.

Experimental Procedure

The experimental proof-of-concept procedure is as follows.

Mass Transfer Rate

The ultrasonic assembly consists of the stainless steel tray and the attached transducer and ultrasonic generator components. It is placed on an electronic balance and the mass is measured to the nearest 2.0 grams. This value is taken as the tare mass.

The liquid to be tested is poured into the stainless steel structure and the mass is also measured to the nearest 2.0 grams.

The transducer/generator assembly is turned on and the timer is started. Measurements are made every 2 to 5 minutes. A time average mass transfer rate can then be calculated. This process is repeated for the various liquids in the experiment.

Vapor Contents

The goal of the experimental setup is to carry the food product, in solution or suspension with the water, into the air stream where it would be subjected to heated air. The water would then be removed. It is therefore necessary to determine if the fine droplets being introduced into the air, carry this food or merely consist of water. The following tests were carried out to determine this.

First, food coloring was dissolved in water and placed in the stainless steel tray. Then the unit was turned on and the resulting mist directed across white filter paper.

In another test, sugar solutions, of known concentrations, were used to quantitatively determine if the mist contained more water and if so, in what concentrations. A sugar solution of known concentration was prepared and placed in the unit. The concentration was verified with a refractometer that was calibrated for sucrose.

The ultrasonic unit was run with the sucrose solution. After half of the mass was transferred from the tray into the air, a sample of the remaining solution was obtained. The concentration of the sucrose in the remaining solution was measured to determine if there was any increase in concentration.

4. Results and Discussion

Mass Transfer Rates

The equipment in Phase I uses two ultrasonic transducers that operate at 1.7 MHz. The resulting mass transfer rates for the test fluids are provided in Table 1. These rates are meant to provide proof of the concept of using ultrasonic energy, and to show the influence of viscosity on the mass transfer rates. Figure 5 shows the relationship between sugar concentration and viscosity. The humidifier setup which was adopted for the Phase I experiment, was constructed to operate most efficiently with pure water. Since the transducers are of fixed frequency and amplitude, the mass transfer rates for the more viscous fluids are lower than for pure water. Figure 6 shows the corresponding relationship between viscosity and mass transfer rate for the ultrasonic assembly that was used in the experiment. Varying the frequencies and amplitudes would yield higher mass transfer rates for the thicker fluids.

TABLE 1 - Mass Transfer Rates

Food Product	Drying Rate (kg/hr)
20% Sucrose Solution	0.135
15% Sucrose Solution	0.140
10% Sucrose Solution	0.210
5% Sucrose Solution	0.216
Tap Water (0% Sucrose)	0.240
Whole Milk	0.060
Skim Milk	0.075
Carrot Juice	0.120
Orange Juice	0.120
Tomato Juice	0.060

Vapor Contents

The initial test for determining the content of the mist, created by the ultrasonic transducers involved filtering the mist that contained the food coloring. After operating the ultrasonic unit for several minutes, the filter paper took on the hue of the food coloring. This was the first stage in verifying that the mist carried more

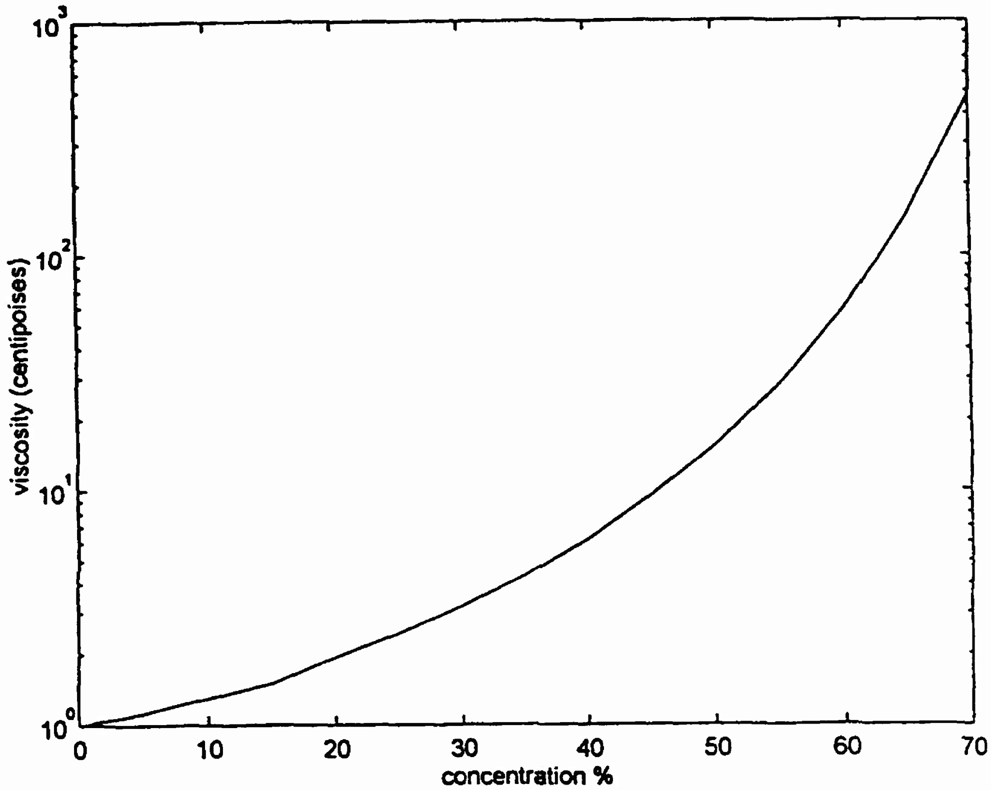

Figure 5. Viscosity Relation of Sucrose Concentration

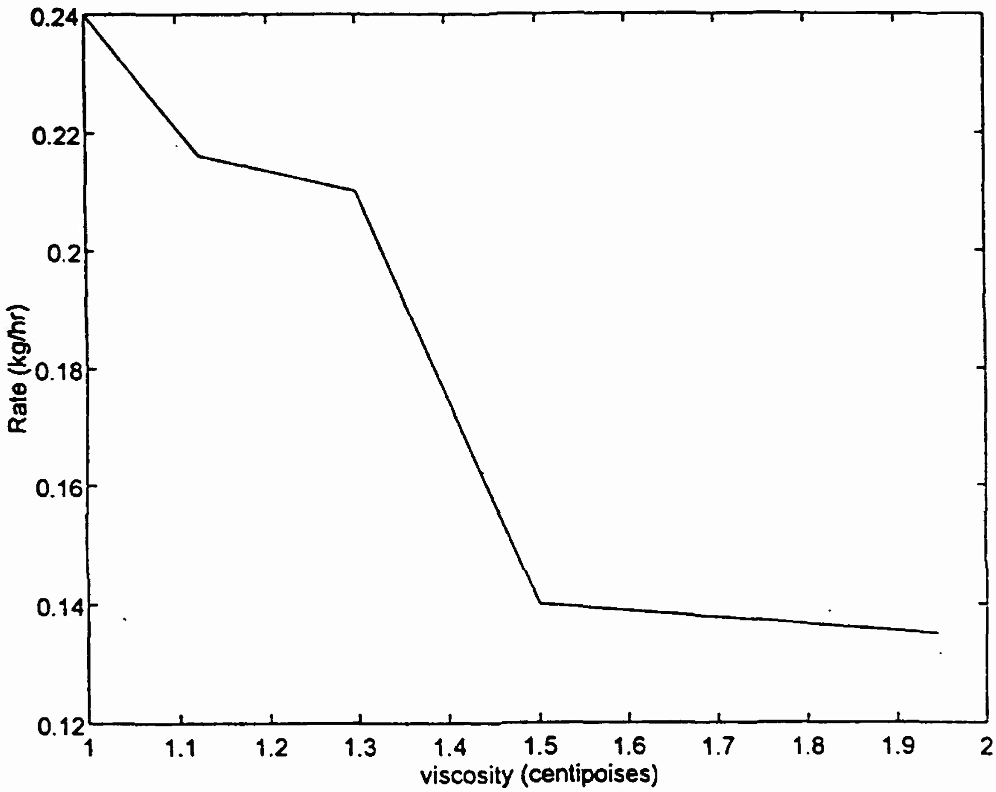

Figure 6. Experimental Rates of Heat Transfer

water than the air stream. The next step was to determine quantitatively what was the content of the mist.

The quantitative measurements were based on a 20% sucrose solution. After half of the mass was transferred into the airstream, the remaining solution was tested using the refractometer. These measurements indicated that the sucrose concentration did not change. This verifies the fact that the tiny droplets released during the process, carry the same components as the fluid in the holding tray. This homogeneity of the liquid is essential if the process is to uniformly transfer the food product into the heated air stream for drying.

Power Requirements

In many dried food products that are used in liquid dental meals, freeze-drying is the primary process used for dehydration (Edinberg and Engell, 1988). The expensive food drying process results in more expensive products. The ultrasonic component of the drying process would run at low power levels. The equipment used in the Phase I experiment removes water at an energy cost of 11.4 watts per kg (25 watts per lb). Typical electric steam generation, i.e. the change of water from a liquid to a gaseous state, requires 156 watts per kg (343 watts per lb). The heat of vaporization of water is 129 watts per kg (284 watts per kg). This heat of vaporization is the minimum amount of energy that is required to convert water to steam. Thus the ultrasonic energy input is only 9% of the minimum energy input possible and 7% of the energy input of pure electrical steam generation. It should be noted that these figures are based on the operation with pure water. For other liquid food products, the energy supplied by ultrasonics would increase but remain at the same order of magnitude:

Conclusions

The favorable results of Phase I indicate that the use of ultrasonic energy, when used with some form of heated air, can improve the dehydration of liquid food products. The primary benefits are as follows.

- The droplets generated by the ultrasonic process are very fine (1 micron diameter) which allows for efficient distribution of food product in the heated air stream.
- The smaller droplet size results in more surface area exposed per volume of fluid, which in turn results in faster heat transfer rates.
- Lower temperatures can be used for the heated air due to the faster heat transfer rates.
- Lower residence times can be achieved due to the faster heat transfer rates.
- The combination of lower temperatures and lower residence times result in a reduction of heat damage to the food products.
- The quality of the processed foods is higher due to reduced heat damage. This reduces the need for nutritive and flavor additives which would normally be used to counteract the heat damage.

5. Recommendations

Construction of Prototype

After the final configuration is determined, the operational prototype will be designed and constructed. Upon completion of the prototype, testing will continue. The actual drying of various food products will begin in order to produce batches for actual quality testing.

Ultrasonic Nozzles

In Phase I the research involved the use of ultrasonic transducers to sonify the liquid food products in bulk form. Two other methods included the sonification of droplets in a suspended or falling state, and the use of ultrasonic nozzles to focus the ultrasonic energy directly. In Phase II these other methods will be investigated. The two methods are closely related in that the ultrasonic nozzles would be most effective if used in conjunction with a suspended or falling fluid. Ultrasonic nozzles would allow the focussing and concentration of the ultrasonic pulses at a specific point, such as a stream of liquid food product. This might yield several advantages over sonification in bulk. First, it could increase the intensity of the sound field, thus allowing for more efficient vaporization of the liquid. Second, it would allow the ultrasonic process to be applied to any pumpable food product. In the case of bulk sonification, there are some fluids which are incompatible with the process. These fluids are those which contain large particles in suspension, such as juices with pulp, or tomato puree with large particles of tomato in suspension. When the cavitation occurs, the small droplets are released into the airstream. If the liquid contains large particles, they will not be carried with the droplets, and will remain in the bulk of the liquid. By using ultrasonic nozzles, this problem can be overcome. If a stream of liquid food product is directed into a field that is created through the use of ultrasonic nozzles, the vaporization can still occur, whether or not the food contains larger particles. In phase II, the details regarding the use of ultrasonic nozzles will be addressed. This includes the following:

- Design of the specific dimensions of the nozzles.
- Determining the optimum configuration of the nozzles with respect to the liquid to be vaporized.
- Determining the ranges of process and liquid food parameters compatible with the ultrasonic nozzles. This includes such parameters as viscosity, amount, and the size of the particles in suspension.

Variable Transducer

For various liquids with different properties, various pressure levels and frequencies are required to produce the cavitation necessary for atomization. In Phase II, TII shall examine the use of transducers and transducer/generator assemblies that are capable of producing ultrasonic fields of varying amplitudes and frequencies. This will not only allow the dehydration assembly to operate on a wider ranges of food products, but it will allow tuning of the process for optimum sonification of the products. Because some products will contain more particles or larger particles, or have greater viscosities, the frequencies of the transducers may need to be higher or the pressure amplitudes larger.

Heated Air

In Phase II the ultrasonic assembly will be designed to include the use of heated air to dry the mist that is produced from the sonification of the liquid food product. The cavitation shall produce very fine droplets of liquid which must be directed into the hot air. The exposure to the heated air should be minimal so the system design should provide for a means of easy collection of the dried product without causing unnecessary heat exposure. One possible approach is a system that uses a partial vacuum to direct the food product away from the heat and into a collection system that is similar to the systems that are used for spray driers.

Supplemental Sonic Fields

One option to be examined as a supplement to the drying system, is the incorporation of an additional sonic field to further reduce the heat that is necessary to dry the food products. In this scenario, the mist that is produced by ultrasonic irradiation of the liquid would be suspended in a sonic field, where additional drying would take place, aided by the added energy of the field. This might reduce the temperature requirements of the heated air or entirely eliminate the need for high temperatures. The process time requirements would be a consideration in the determination of the feasibility of this approach.

Product Quality Evaluation

The quality of foods can be defined as those attributes that make it fit for the intended purpose. Food quality can also be defined in terms of a large number of properties. The many factors that combine to determine the quality are of different importance from one food to another. For one product the flavor may be the deciding factor, while consistency, texture, appearance, nutritional value or some other factors may be the most important in other products.

Upon successful dehydration of the foods by ultrasonics, the control as well as the dried foods, will be evaluated by physical, chemical microbiological and sensory tests. Since the length of the shelf-life of either fresh, or processed foods, depends on the storage conditions such as temperature, humidity, etc., and the packaging methods, tests will be conducted to determine the effect of these variables on the nutritional and sensory acceptability of the ultrasonically dried foods.

Physical Analyses

Physical analyses will include color, texture, density, equilibrium moisture content, rehydration ratio, reconstitution properties and sensory analysis.

Color

The three major attributes of the quality of foods are color, flavor and texture. All three are important, but color and appearance or "total visual impact" is the factor that determines if the food is appealing to the consumer. A food must sell itself, and if its visual impact is negative, the consumers may never get to evaluate the flavor and texture, and the product may remain on the shelf. The color of the processed foods will be evaluated with instrumental procedures and through human subject tests.

Texture

According to the Taste Testing and Consumer Committee for the Institute of Food Technologists, "Texture is the totality of those properties of a food stuff apprehended by eyes and by the skin and muscle senses in the mouth after injection of a solid or liquid food." It relates to density, viscosity, surface tension, and other physical properties of the material being sampled. In relation to food materials, textural characteristics are a function of moisture, fat cohesiveness, hardness, fluidity, elasticity, adhesiveness, brittleness, chewiness and gumminess. The units in which these characteristics are measured are usually a function of the instrument that is employed to measure them and therefore, may be empirically related to the structural quality of the material. The main purpose of assessing texture of food is to determine the effort that is required by the mouth to disintegrate and swallow the material. The texture assessment can be quantitative or simply a qualitative categorization of the foods that is given by the test subjects.

Equilibrium Moisture Content (EM)

This is the lowest moisture content that can be achieved in the dehydration of foods under a set of given conditions of temperature and humidity. In engineering terms, it is defined as the moisture content that exists when the material is at vapor pressure equilibrium with its surroundings. In the dehydration process this represents the moisture of the product which is approached at the completion of the drying. The magnitude of the EM is established by the structure of the material and the manner in which the water is held or bound by the product. The EM varies with the food product. In Phase II many different products will be tested. Some will contain solids in solution and would yield a low-moisture content when dehydrated. Others will contain larger, non-soluble particles such as fruit pulp, and would yield a higher moisture content after processing. The various limits on the moisture content that is imposed by the military will be examined and the ultrasonically dehydrated products will be tested accordingly.

Rehydration (Reconstitution) Properties

Reconstitution properties are measured in terms of the rehydration ratios. One definition of the rehydration ratio is the ratio of the mass of water regained to the mass of the water lost during drying. Another definition is the ratio of the mass of the rehydrated food to the mass of the dehydrated food. After dehydrating the food products via the UDS, the products will be reconstituted and the specific procedures will be outlined according to the specific food and its properties.

Sensory (Organoleptic) Evaluation

Foods are submitted to sensory examination to provide information that can lead to product improvement, quality maintenance, the development of new products, or analysis of the market. Sensory tests may be conducted to:

- Select qualified judges and study human perception of food attributes
- Correlate sensory measurements with chemical and/or physical measurements
- Study processing effects
- Evaluate quality
- Determine consumer reaction

Each of these purposes requires appropriate tests. In general, laboratory panels are used for the first three purposes, highly trained experts for the fourth and large consumer groups for the last.

Chemical Analyses

Chemical analyses include the examination of protein, lipids, carbohydrates, vitamins, minerals and flavor components. Thermal processing during the dehydration of foods provides important methods for extending the storage life of foods. The basic function of a thermal process, wherein the temperature of the product is elevated above ambient temperature, is to eliminate or reduce the microorganisms and/or enzymes that would result in deterioration of the food on storage. However, during thermal processing of foods, concomitant with the reduction of microorganisms and inactivation of spoilage causing enzymes, is the simultaneous effect of heating on proteins, lipids, carbohydrates, vitamins, minerals and flavors. The quantitative analysis of these would be carried out by a certified laboratory. Samples of the original product and the dehydrated/reconstituted product would be analyzed to insure that accurate comparisons determinations of nutrient loss were made.

Process Economics

After the final design is determined, TII will examine the operation cost of the process and compare it to existing processes such as freeze-drying and spray drying. The economy of the process should be evaluated along with the product quality. If the costs of the operation are comparable to existing processes and the ultrasonic process results in considerably higher quality foods because of the reduction of heat damage, then the ultrasonic process would be favorable.

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6. References

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APPENDIX

DEHYDRATION METHODS

Drying by Heated Air (Convection)

The food is placed in contact with a moving stream of heated air. Heat is mainly supplied to the product by convection.

In air drying, the rate of removal of water depends on the conditions of the air, the properties of the food, and the design of the dryer.

Moisture can be held in varying degrees of bonding, ranging from the extremes of moisture that lie on the surface to moisture that is bound with other constituents. In drying, it is obvious that the water which is loosely held, will be removed most easily. Thus, it would be expected that the drying rates would be slower as the moisture content decreases. The remaining water is bound more and more strongly as its quantity decreases.

In many cases a substantial portion of the water is found to be loosely bound. For drying purposes this part can be considered to be free water at the surface. We may then compare drying rates for a material such as sand with those of a food such as meat.

This behavior in which the drying behaves as though the water is at a free surface, is termed constant rated drying. However, food, unlike sand, contains water and, after a period of drying at a constant rate, the water comes off more slowly. The change from a constant drying rate to a slower drying rate occurs at a different moisture constant for different foods. Although there is a variation with protein and carbohydrate that is constant for different foods, the change from the constant drying rate occurs at a moisture content that is in equilibrium is at 58 to 65% relative humidity. The moisture content at which this change of rate occurs is known as the critical moisture constant.

Another point of importance is that many foods, such as potatoes, do not show a time constant rate drying period. However, they do show quite a sharp break in the drying curve after a slowly declining drying rate period. The concept of constant rate is still a useful approximation. In some cases, there may be more than one constant rate period.

The end of the constant rate period, the break point of the drying rate curves, signifies that water has ceased to behave as a free surface and factors other than vapor pressure differences are controlling the rate of drying. Thereafter, the drying rate decreases. This is termed the falling rate period of drying. The factors that control the falling rate period are complex. It depends upon diffusion through the food and upon the changing energy binding patterns of the water molecules.

Calculation of Constant Rate of Drying

In the constant rate period the water is being removed from the equivalent of a free water surface. The rate of removal of the water is governed by the rate of heat transfer from the air to the surface water, and by the partial vapor pressures of water at the surface and in the air stream.

The rate of heat transfer, assuming that radiation and conduction are negligible is given by:

$$Q = h_c A(t_a - t_s) \qquad (1)$$

Where: Q = rate of heat transfer

h_c = convective heat transfer coefficient

A = drying area

t_a = temperature of the air

t_s = temperature of the drying surface

When drying is proceeding, the rate of heat transfer can be related to the rate of mass transfer of the water into the air stream. The rate of mass transfer is given by:

$$W = k_g A(p_s - p_a) \qquad (2)$$

Where: W = mass of water being transferred per unit time

k_g = mass transfer coefficient

A = drying area

p_s = partial pressure of water vapor at the surface

p_a = partial pressure of water vapor in the air

This can also be written as:

$$W = k_g A(H_s - H_a) \qquad (3)$$

Where: H_s = humidity of the air at saturation

H_a = humidity of the air

Also, where instant heat must be applied to the evaporating water, we can write:

$$W \ \lambda = Q \qquad (4)$$

Where: λ = latent heat of vaporization of water

Combining these equations we have:

$$W = k_g A(p_s - p_a) = [h_c A\ (t_a - t_s)]/\lambda \qquad (5)$$

Rearranging (5) gives:

$$k_g = [h_c(t_a - t_c)]/[\lambda(p_s - p_a) \qquad (6) \text{ and:}$$

$$h_c = [\lambda k_g(p_s - p_a)]/(t_a - t_s) \qquad (7)$$

It is not easy to measure mass transfer coefficients and they are often predicted indirectly by using the dimensionless Lewis Number group:

$$L_N = h_c/k'_g c_p \qquad (8)$$

The above analysis holds good for foods in the early stages of drying. when drying proceeds beyond this point, the rate decreases. In order to predict further drying rates, the way in which the water is associated with the other constituents of the foods must be considered.

From this analysis, it may be seen that the constant drying rate is affected by:

- Air temperature (The difference between this and the surface temperature is the driving force affecting mass transfer.)
- The velocity of the air which affects h_c
- The surface area that is exposed to the air.

The surface temperature in air drying can be taken, for all practical surfaces as the wet bulb temperature. The character of the material influences the constant drying rate because it determines the equilibrium vapor pressure relationship.

Drying by Direct Contact with a Heated Surface (Conduction)

Heat is supplied to the product mainly by conduction. This heat provides the latent heat of vaporization of the water. The drying proceeds independently of the condition of the air. A heat balance is set up between the heat transferred with the food and the heat lost by *evaporation* of the water and also by convection and conduction to the air.

$$Q = UA(t_h - t_s) \qquad (9)$$

Where: Q = rate of heat transfer

U = overall heat transfer coefficient

A = area through which heat transfer and drying occurs

t_h = temperature of heating medium

t_s = temperature of food being dried.

Freeze-drying

In freeze-drying, the transfer of heat to the drying zone may proceed by conduction or by radiation or, most likely, a combination of both. The control of the rate of heat transfer is most important. It is necessary to avoid the melting of ice, so the rate of heat transfer must be low enough to ensure this. On the other hand, to accomplish the drying operation in a reasonable time, the rate of heat transfer must be as high as possible. The accomplishment of this maximum safe rate of heat transfer is a major objective in the design of efficient freeze-drying equipment. Also the surface temperature must not rise so high as to cause deterioration of the food material at the surface.

Among the advantages commonly associated with the freeze-drying process are:

- Freezing stops virtually all bacterial and enzymatic action in most food products.
- The molecular constituents remain in their original orientation during drying.
- There is little or no change in volume during drying.
- The "mild" conditions of drying assure the minimum loss of labile and volatile nutritional constituents.
- The end products are light in weight (with only the solids remaining).
- More of the nutrients, taste, and flavor constituents remain, than with any other known industrial drying process.